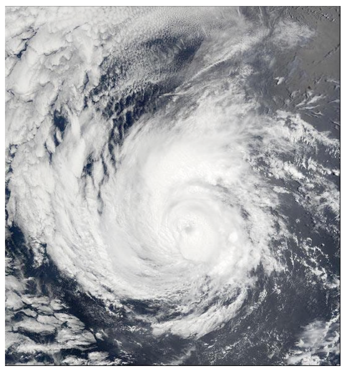
# Chapter 2. Weather and Climate

## The Structure of the Atmosphere

Surrounding the Earth is a gaseous envelope or atmosphere, held in place by the planet's gravitational attraction. The Earth's atmosphere is a complex dynamical, physical, and chemical system. Dynamic processes cover a large range of scales from the microscopic-scale dynamics of evaporation, condensation, cloud formation and precipitation, to small-scale, localized vertical and horizontal wind motions, to medium-scale cyclones, anticyclones, hurricanes, typhoons, tornadoes, thunderstorms, fronts, etc., to the large-scale general circulation of the atmosphere.



Physical processes in the atmosphere include the transfer of incoming solar radiation through the atmosphere to the surface, the heating of the surface, the emission of outgoing infrared radiation, the absorption of infrared radiation by atmospheric gases, the evaporation of water, the condensation of atmospheric water vapor into clouds, and precipitation. Chemical processes include the transformation and production of atmospheric gases, such as atmospheric ozone, via chemical reactions involving many dozens of gases in the atmosphere.

While the Earth's atmosphere extends upward for hundreds of kilometers until it merges with interplanetary space, more than half of the atmosphere's total mass is below an altitude of only about 6 kilometers (3.75 miles) above the surface (Figure 2-1). The lowest region of the atmosphere, the troposphere, extends from the surface to an altitude that varies from 10 to 15 kilometers (km) (6.2 to 9.3 miles (mi.)), depending on latitude and season. The top of the troposphere is called the tropopause. The regions of the atmosphere above the troposphere are the stratosphere (from between 10 and 15 to 40 km (between 6.2-9.3 and 25 mi.)), the mesosphere (40 to 80 km (25 to 50 mi.)), the thermosphere (80 to 500 km (50 to 310 mi.)) and the exosphere (begins at about 500 km (310 mi.)). The exosphere merges with interplanetary space. The ionosphere is the region of atmosphere between 40 and 300 km (25 and 185 mi.). It is the region of positively-charged atoms and molecules and negatively-charged electrons.

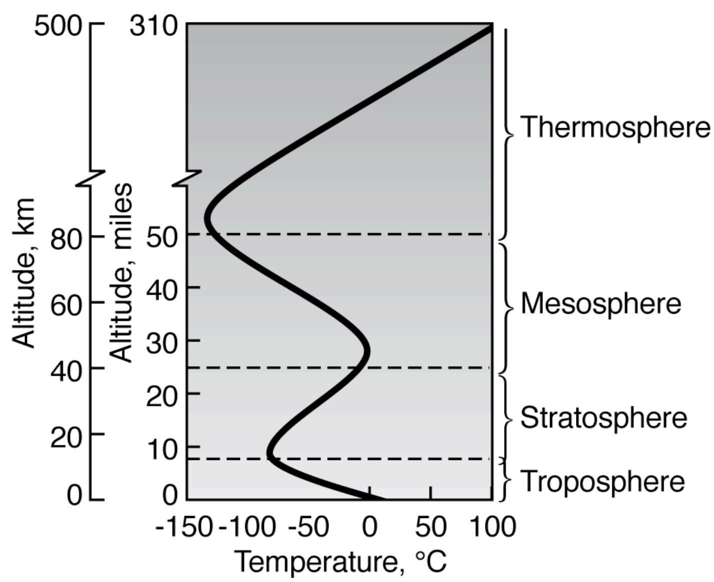



**Figure 2-1. Regions of the atmosphere.**

## The Chemical Composition of the Atmosphere

The Earth's atmosphere is a complex mixture of gases: nitrogen ($N_2$) (about 78% by volume), oxygen ($O_2$) (about 21% by volume) and argon (Ar) (about 0.9% by volume) with small and varying amounts of water vapor ($H_2O$) (0 to 4% by volume) and still smaller amounts of carbon dioxide ($CO_2$), methane ($CH_4$), nitrous oxide ($N_2O$), ozone ($O_3$) and dozens of other gases at still smaller concentrations. The chemical composition of the atmosphere is given in Table 2-1. The protection afforded by the atmosphere is very important for life on Earth. The atmosphere shields the Earth's surface and its myriad forms of life from biologically damaging high-energy cosmic radiation. In addition, ozone, found mostly in the stratosphere, absorbs ultraviolet radiation from the Sun, shielding the Earth's surface from this biologically damaging radiation.

**Table 2-1. Chemical Composition of the Earth's Atmosphere**

| Gas | Concentration* |
|---|---|
| Nitrogen ($N_2$) | 78.084% |
| Oxygen ($O_2$) | 20.946% |
| Argon (Ar) | 0.934% |
| Carbon Dioxide ($CO_2$) | 0.037% |
| Water Vapor ($H_2O$) | 0.01 to 4%† |
| Neon (Ne) | 18.2 ppmv |
| Helium (He) | 5.0 ppmv |
| Methane ($CH_4$) | 1.8 ppmv |
| Krypton (Kr) | 1.1 ppmv |
| Hydrogen ($H_2$) | 0.5 ppmv |
| Nitrous Oxide ($N_2O$) | 0.5 ppmv |
| Xenon (Xe) | 0.09 ppmv |
| Ozone ($O_3$) | 0.0 to 0.07 ppmv† |
| Nitrogen Dioxide ($NO_2$) | 0.02 ppmv |

*Concentration units: % or parts per million by volume (ppmv) (1 ppmv = 0.0001%).

†Highly variable.

The mean molecular mass of dry air is 28.97 atomic mass units or Daltons.

## Instruments to Measure Weather

**Weather** is the instantaneous or current state of the atmosphere and is measurable in terms of temperature, atmospheric pressure, humidity, wind speed and direction, cloudiness and precipitation. **Climate** is the state of the atmosphere over long time periods, such as over years, decades, centuries or greater. In general, the weather that impacts the surface of the Earth and those that live on the surface takes place in the troposphere. Weather parameters are measured with different instruments. Atmospheric temperature is measured with a thermometer.

**Atmospheric pressure** is a measure of the force exerted by the mass of atmosphere on the surface at a given location. The average pressure of the atmosphere at mean sea level is about 1 kg per square cm, which is equivalent to about 14.7 pounds per square inch or a pressure of 1013.25 millibars (mb), and which is also referred to as 1 atmosphere. Atmospheric pressure is measured with a barometer.

**Humidity** is a general term that refers to the water vapor content of the air. **Absolute humidity** is the actual amount of water vapor per volume of air. **Relative humidity** is the percentage of water vapor in the atmosphere compared with the maximum amount of water vapor that the atmosphere could contain at that temperature. The dew point of a given parcel of air is the temperature to which the parcel must be cooled, at constant pressure, for the water vapor component to condense. Humidity is measured with a psychrometer.

**Wind speed** is measured with a 4-cup anemometer and **wind direction** is measured with a weather vane. Winds are named after the direction from which they flow. For example, the northeast trade winds flow in a southward direction from the northeast. The amount of **cloud cover** is estimated either visually or photographically. The amount of **precipitation** is measured with a rain gauge.

## *Solar Radiation, the Greenhouse Effect and the Temperature of the Earth*

To a large extent, the temperature of the Earth's surface is determined by the amount of radiation received from the Sun. Most of the incoming radiation from the Sun is in the form of visible radiation.

The atmosphere is mostly transparent to incoming solar radiation, i.e., this radiation is not absorbed by gases in the atmosphere, with the notable exception of solar ultraviolet radiation, which is absorbed by ozone mostly located in the stratosphere. However, some of the incoming solar radiation is reflected back to space by clouds (Figure 2-2), by ice and snow at the poles, and by desert areas. The surface of the Earth is heated by the absorption of incoming solar radiation and reaches a mean global temperature of about –18 °C (0 °F). Once heated to the mean temperature, the Earth emits radiation in the form of "long-wavelength," or infrared, radiation back to space. Unlike incoming solar radiation, which is not strongly absorbed by atmospheric gases and passes through the atmosphere to the surface, outgoing infrared radiation is strongly absorbed by several different atmospheric gases, including carbon dioxide, water vapor, methane, nitrous oxide and ozone.

Immediately after being absorbed by these atmospheric gases, the infrared radiation is quickly re-emitted or released back to the atmosphere in both the upward and downward directions. The downward component of the re-emitted infrared radiation strikes the surface and causes additional heating, increasing the mean temperature of the Earth to about 15 °C (59 °F). This additional heating is called the "greenhouse effect" and the gases that absorb and then re-emit infrared gases are called "greenhouse gases." Measurements show that atmospheric concentrations of greenhouse gases — carbon dioxide, methane and nitrous oxide — are increasing with time most probably due to human activities. Atmospheric concentrations of water vapor will increase as the temperature of the atmosphere increases. The buildup of greenhouse gases in the atmosphere has led to national and international concern about global warming and its accompanying environmental consequences.

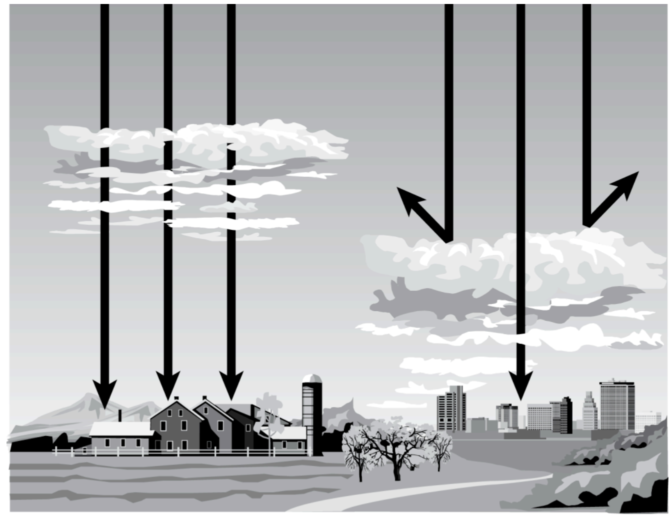


**Figure 2-2. Transfer of incoming solar radiation through the atmosphere.**

The Intergovernmental Panel on Climate Change (IPCC) released its Fourth Assessment Report in February 2007 with the following conclusions:

- Warming of the climate system is unequivocal.
- Most of the observed increase in globally averaged temperatures since the mid-20th century is very likely due to the observed increase in anthropogenic greenhouse gas concentrations.
- Hotter temperatures and rises in sea level "would continue for centuries" no matter how much humans control their pollution.
- The probability that this is caused by natural climatic processes alone is less than 5%.
- World temperatures could rise from anywhere between 1.1 and 6.4 °C (1.98 to 11.52 °F) with a corresponding sea level rise of 18 to 59 centimeters (cm) (7 to 23 inches (in.)) during the 21st century.

## Solar Heating and Atmospheric Motion

Weather is a very complex phenomenon and is controlled by many factors and processes, such as the heating of the Earth's surface and atmosphere by incoming solar radiation. Incoming solar radiation is absorbed by the Earth's surface, which in turn warms the lower atmosphere. Because warmer air is less dense than cooler air, the heated air will begin to rise through the atmosphere. The rising air creates a low-pressure area at the surface. The background, or ambient, temperature of the atmosphere decreases with altitude (Table 2-2) as the distance from the Sun-heated surface increases. The decreased atmospheric temperature with altitude causes water vapor in the rising air mass to cool to its dew point, which leads to condensation, the formation of cloud droplets and clouds and maybe eventually precipitation. Hence, rising air masses and low-pressure areas at the surface are usually associated with clouds and, possibly, stormy conditions (Figure 2-3). Severe weather phenomena, such as thunderstorms, tornadoes and hurricanes are all associated with rising air motions and accompanying low-pressure surface areas. Regions of descending or falling air cause high-pressure areas at the surface, and, in general, bring cloud-free and fair weather conditions. Areas of low and high pressure at the surface, caused by rising and falling air parcels, can vary in diameter from a few meters to hundreds of kilometers.

**Table 2-2. The Variation of Mean Atmospheric Temperature and Pressure with Altitude**

| Altitude, km (miles) | Temperature, °C (F) | Pressure, millibars (pounds per inch) |
|---|---|---|
| 0 | 15.0 (59.0) | 1013.25 (14.696) |
| 1 (0.62) | 8.5 (47.3) | 899 (13.038) |
| 2 (1.24) | –2.0 (28.4) | 795 (11.530) |
| 3 (1.86) | –4.5 (23.9) | 701 (10.167) |
| 4 (2.48) | –11.0 (12.2) | 616 (8.934) |
| 5 (3.11) | –17.5 (0.5) | 540 (7.832) |
| 6 (3.73) | –24.0 (–11.2) | 472 (6.846) |
| 7 (4.35) | –30.5 (–22.9) | 411 (5.961) |
| 8 (4.97) | –37.0 (–34.6) | 356 (5.163) |
| 9 (5.59) | –43.5 (–46.3) | 307 (4.453) |
| 10 (6.20) | –50.0 (–58.0) | 264 (3.829) |
| 11 (6.83) | –56.5 (–69.7) | 226 (3.278) |
| 12 (7.46) | –56.5 (–69.7) | 193 (2.799) |
| 13 (8.08) | –56.5 (–69.7) | 165 (2.393) |
| 14 (8.70) | –56.5 (–69.7) | 141 (2.045) |
| 15 (9.32) | –56.5 (–69.7) | 120 (1.740) |

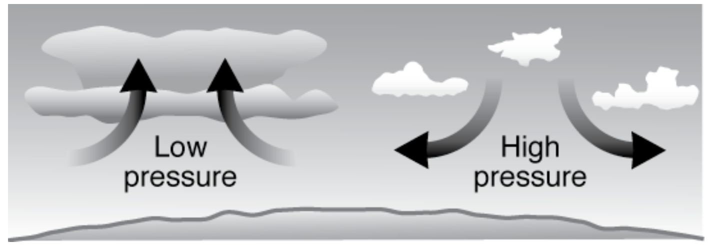



**Figure 2-3. Rising air masses and low-pressure areas are usually associated with clouds and stormy conditions, while descending air and high-pressure areas at the surface usually mean fair weather conditions.**

## Cyclones and Anticyclones

A cyclone is a low-pressure weather system. The air above a cyclone rises, leading to the formation of clouds and possibly precipitation. In the northern hemisphere, a counterclockwise rotation develops around the cyclone center. In the southern hemisphere, a clockwise rotation develops around a cyclone. The weather is usually stormy within low-pressure areas. An anticyclone is a high-pressure weather system. The air above an anticyclone descends. In the northern hemisphere, a clockwise rotation develops around the anticyclone center. In the southern hemisphere, a counterclockwise rotation develops around an anticyclone. In general, the weather is usually clear and good within high-pressure areas.

A hurricane is a tropical cyclone. Hurricanes are energized by heat released when moist air rises and the water vapor in the rising air condenses. Hurricanes are born and sustained over large bodies of warm water and lose their power over land where the source of their energy, the condensation of water vapor, is significantly reduced. Hurricanes can produce extremely strong winds, tornadoes, torrential rain, high ocean waves and storm surge. A hurricane has sustained winds of at least 119 km per hour

(74 miles per hour). A hurricane is a very energetic phenomenon with energy release estimated to be the equivalent of exploding a 10-megaton nuclear bomb every 20 minutes or about 200 times the worldwide electrical generating capacity per day. Although hurricanes are large weather systems generating enormous energy, their movements over the Earth's surface are controlled by large-scale atmospheric winds. Recently, it has been suggested that both the numbers and intensity or energy of hurricanes will increase as a consequence of global warming.

## Variations in Surface Atmospheric Pressure

The mean sea level atmospheric pressure is about 1013.25 millibars (mb) or 14.7 pounds per square inch (psi). A moderate cyclone has a surface pressure of about 995 mb. A very strong cyclone has a surface pressure of about 975 mb. Hurricane Camille in 1969 had a surface pressure of 908 mb. The lowest recorded sea level pressure was 870 mb associated with a Pacific typhoon on October 12, 1979. A moderate anticyclone has a surface pressure of about 1030 mb. A very strong anticyclone has a surface pressure of about 1050 mb. The highest recorded sea level pressure was 1084 mb over Agata, Siberia, on December 31, 1968. The decrease of atmospheric pressure with altitude is shown in Table 2-2.

## Air Masses and Fronts

An air mass is a large body of air with nearly uniform temperature and humidity that moves mostly in the horizontal direction. In general, air masses derive temperature and humidity characteristics from the

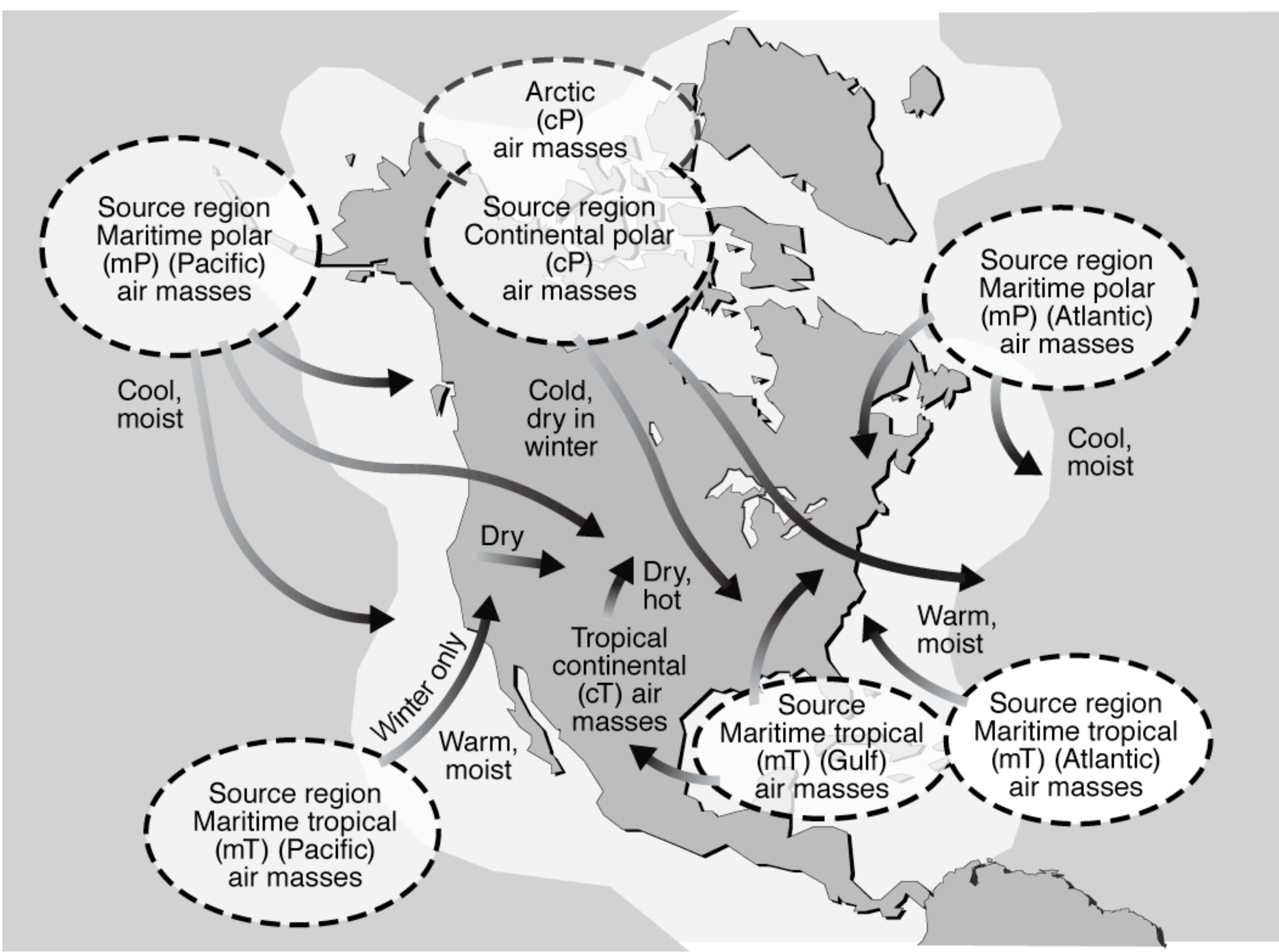



**Figure 2-4. Source regions of air masses.**

regions in which they originate, which are called the air mass source regions (Figure 2-4). Typically, air masses are classified first according to temperature: polar (from between 50° and 65° latitude), tropical (from 20° to 35° latitude) and equatorial (from over the oceans near the equator). Polar (P) air masses are cold; tropical (T) air masses are warm. Then, air masses are classified either moist or dry depending upon whether the source region is land or water. Maritime (m) air masses form over the oceans and are relatively moist; continental (c) air masses form over land and are relatively dry. A maritime tropical air mass is designated as mT, while a continental polar air mass is designated cP. Fronts are the boundaries between two different interacting air masses. A cold front occurs when a cooler air mass moves in on a warmer air mass. A warm front occurs when a warmer air mass moves over a cooler air mass. A stationary front is a front that exhibits little or no movement.

## General Circulation of the Atmosphere

Due to the curvature of the Earth (the Earth's sphericity), the Sun's rays are spread over a larger and larger area the further the latitude from the equator. Therefore the sunlight is less concentrated than at latitudes nearer the equator and less solar heating takes place. This is why the Earth's equatorial regions are hot and the polar regions are cold. The atmosphere and ocean redistribute the excess solar energy from the equatorial regions to the polar regions via their circulation (Figure 2-5). Hence, the solar-heated air at the equator rises and then moves poleward at high altitudes in both hemispheres. This causes a surface low-pressure area at the equator. The low-pressure area between 5° N and 5° S is called the Intertropical Convergence Zone (ITC). At about 30° N and 30° S of the equator, some of the high-altitude, poleward-moving heated air begins to cool, which

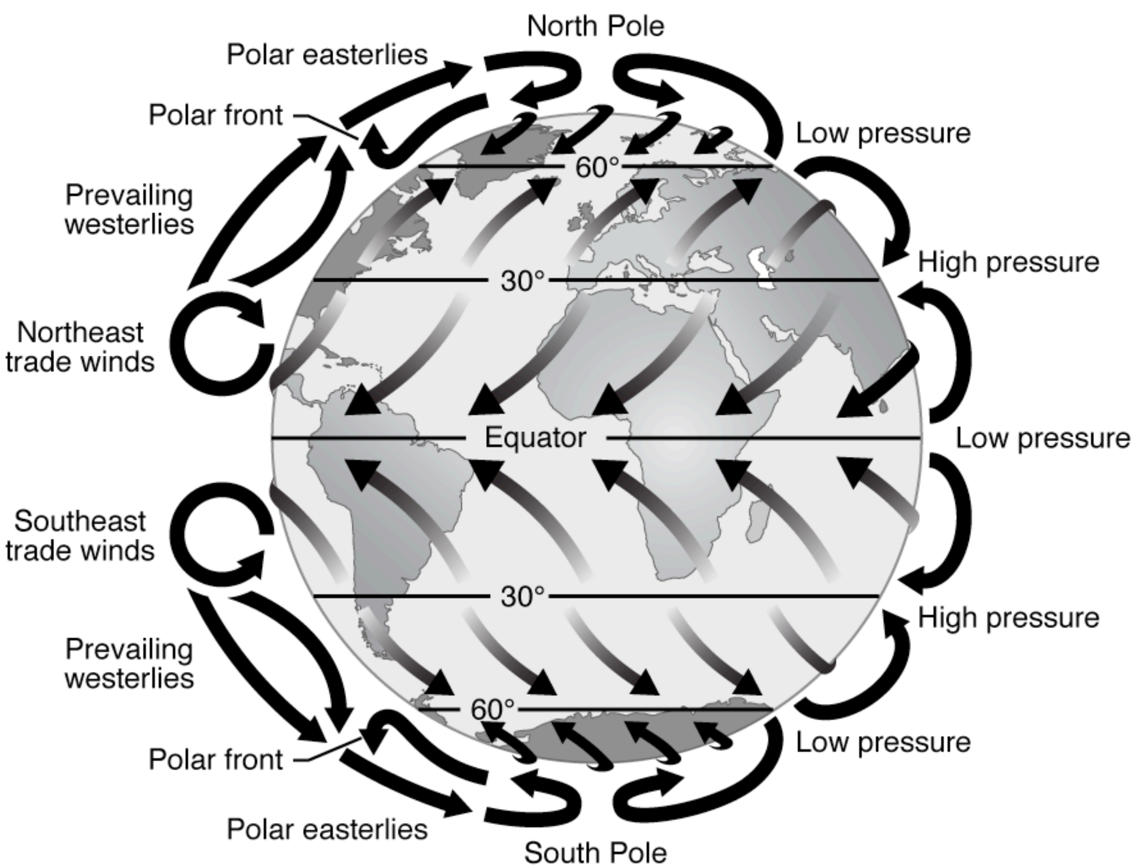



**Figure 2-5. The general circulation of the atmosphere.**

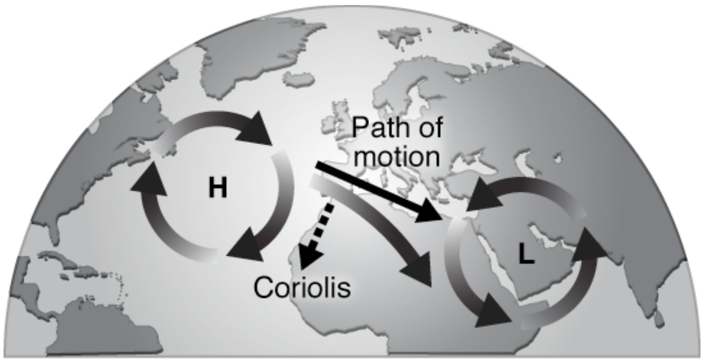


Figure 2-6. The Coriolis Effect.

causes it to descend to the surface, creating high-pressure areas at the surface. The descending air sets up surface wind patterns that flow away from these high-pressure systems towards the poles and the equator in both hemispheres. As air flows from regions of high pressure to regions of low pressure, it is deflected to the right (in the northern hemisphere) and to the left (in the southern hemisphere) by the Earth's rotation. This is known as the Coriolis Effect (Figure 2-6). Thus, in the northern hemisphere, the surface air flowing equatorward is turned toward the southwest. These winds are called the northeast trade winds because they blow from the northeast (toward the southwest). In the southern hemisphere, the surface air flowing equatorward is turned toward the northwest. These winds are called the southeast trade winds because they blow from the southeast (toward the northeast). In both the northern and southern hemispheres, the poleward surface flow gets directed by the Coriolis effect, resulting in westerly or prevailing westerly winds. The general flow of the atmosphere begins to get more complicated poleward of 30° in both hemispheres due to the presence of fronts and the high-altitude jet stream. In the northern hemisphere, the flow of the prevailing westerlies is further disturbed by the presence of land masses. Weather, particularly poleward of 30°, is also impacted by dissimilar and interacting large air masses forming fronts and surface cyclones and anticyclones.

The El Niño-Southern Oscillation (ENSO) is a global-coupled ocean-atmosphere phenomenon. El Niño and La Niña are major temperature fluctuations in the surface waters of the tropical eastern Pacific Ocean. Their effect on climate in the southern hemisphere is significant. In the Pacific Ocean, during major warming events, El Niño warming extends over much of the tropical Pacific. The specific mechanisms responsible for the El Niño ocean warming are not known.

Jet streams are high-speed bands of winds in the upper troposphere that flow west to east over both the northern and southern hemispheres (Figure 2-7). The winds in the jet stream are variable and may reach 500 kilometers per hour (310 miles per hour). In winter, the average speed is 160 kilometers per hour (100 miles per hour); in summer, the average speed is 80 kilometers per hour (50 miles per hour). The location of the jet stream may move equatorward and poleward from week to week. This movement of the location of the jet stream "steers" fronts at the surface and hence, greatly impacts local weather over the Earth. When the jet stream dips down to the southeast U.S., colder than normal temperatures often cover the eastern half of the country, while warmer than normal temperatures often prevail in the western half of the country.

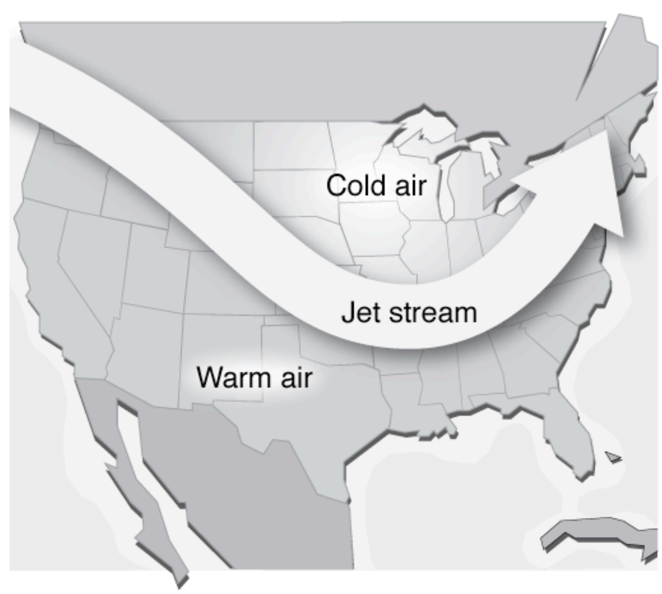


Figure 2-7. The jet stream over North America.

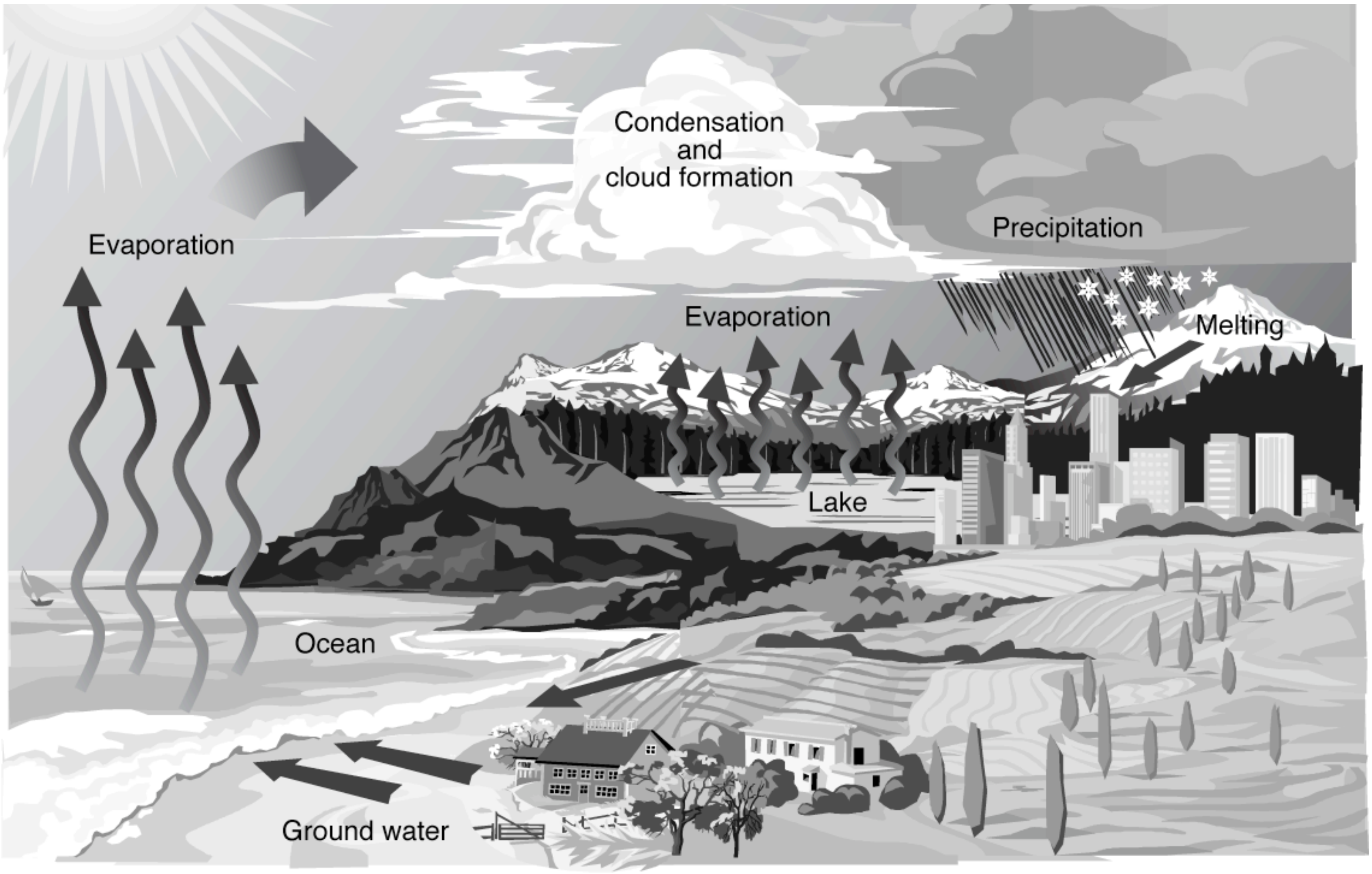



**Figure 2-8. The water cycle.**

## *The Water Cycle and Clouds*

The **water cycle** (Figure 2-8) was already briefly mentioned in relation to the condensation of water vapor and the formation of cloud droplets and eventually precipitation in rising air masses.
The three main elements of the water cycle are **evaporation**, **condensation** and **precipitation**. **Evaporation** is the process of transforming liquid water in the oceans and in the soil to water vapor, an invisible, odorless gas that enters the atmosphere. **Condensation** is the process of changing gaseous water vapor back to liquid water and in the process forming cloud droplets. As the water vapor rises in the atmosphere, atmospheric temperature decreases with altitude and condensation begins, resulting in the formation of tiny cloud droplets. The tiny cloud droplets begin to collide and coalesce with neighboring cloud droplets, growing in size and weight and eventually forming **precipitation**, which “falls” out of the atmosphere as liquid water droplets (rain) or solid water particles (snow and hail).

Other processes in the water cycle are freezing, melting and sublimation, which all involve changing the state of water. Sublimation is the change of phase from a solid to a gas without the intermediate step of forming liquid. In the case of water, sublimation is the change from snow or ice to gaseous water vapor, without the intermediate step of forming liquid water.

Cloud condensation nuclei (CCN) are very small particles (typically about 1/100th the size of a cloud droplet) upon which cloud droplets coalesce. To make a transition from the gaseous state of water vapor to the liquid water droplet, a nongaseous surface is required. In the atmosphere, tiny solid or liquid CCN particles provide this surface.

Clouds are visible masses of condensed droplets or frozen crystals suspended in the atmosphere above the surface. Clouds are divided into two main categories: convective or cumulus clouds (in Latin, cumulus means piled up) and layered or stratus clouds (in Latin, stratus means layer). Cumulus and stratus clouds are divided into four more groups that distinguish the altitude location of the cloud. The family of low clouds (found up to 2 km (6,500 ft)) includes **stratus**, **nimbostratus**, **cumulus**, and **stratocumulus**. **Cumulus** clouds (Figure 2-9) are dense, white and puffy, resembling cotton balls. Cumulus clouds are found either as single clouds or closely packed clouds. While cumulus clouds resemble puffy white cotton balls and are associated with good weather, **stratus** clouds (Figure 2-10) are dark gray, low, uniformly stratified or layered covering the entire sky and are usually associated with rain. Middle clouds are found between 2 and 5 km (6,500 and 16,500 ft). Middle clouds are denoted by the prefix "alto" and include altostratus and altocumulus. High clouds are found above 5 km (16,500 ft) in the cold region of the troposphere and are denoted by the prefix "cirro" or cirrus. At this altitude, water freezes so the clouds are almost always composed of ice crystals. These clouds are wispy and often transparent. High clouds include cirrus, cirrostratus and cirrocumulus. Aircraft contrails form in this altitude range. Vertical clouds have strong upward currents and form over a wide altitude range and include cumulonimbus, which are very large, towering dark clouds usually associated with heavy precipitation and thunderstorm activity.

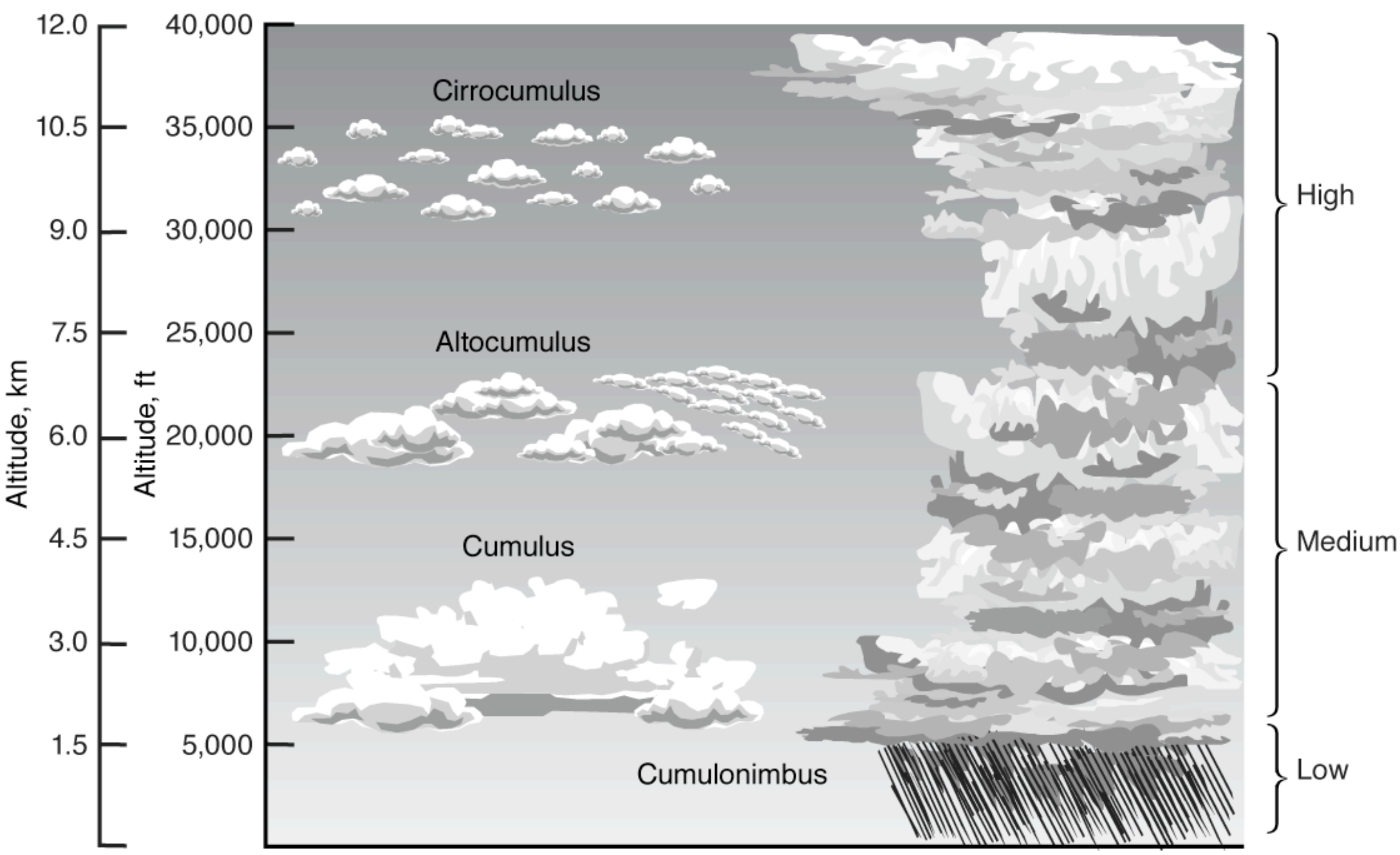



**Figure 2-9. Cumulus clouds.**

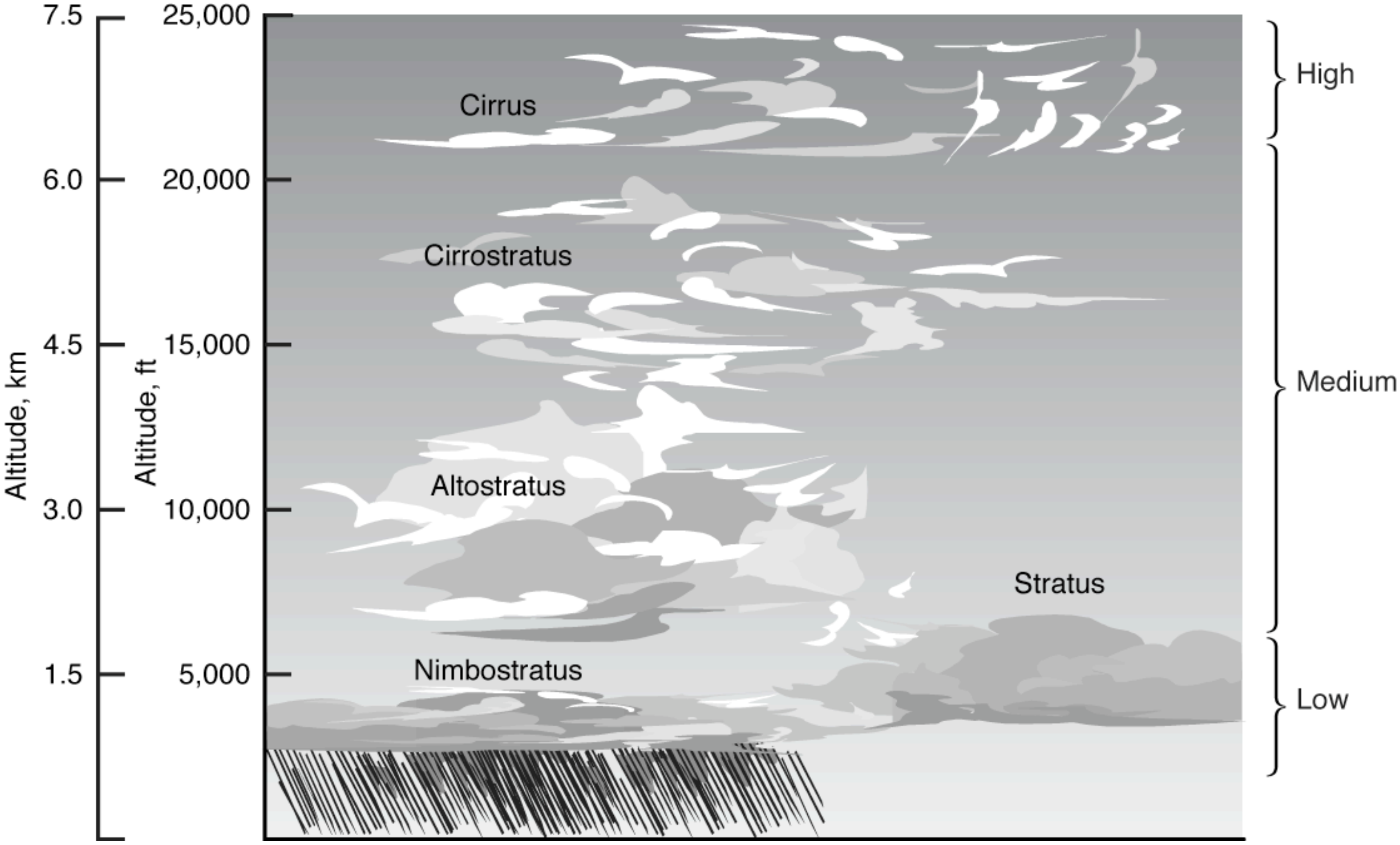



**Figure 2-10. Stratus clouds.**